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Date: 2017-11-10T00:00:00+00:00

Abstract

We take the JUNO experiment as an example to explore nuclearites in the future large liquid scintillator detector. Comparing to the previous calculations, the visible energy of nuclearites across the liquid scintillator will be reestimated for the liquid scintillator based detector. Then the JUNO sensitivities to the nuclearite flux are presented. It is found that the JUNO projected sensitivities can be better than 7.7×10−17cm−2s−1sr−1 for the nuclearite mass 1015 GeV M 1024 GeV and initial velocity 10−4 0 10−1 with a 20 year running. Note that the JUNO will give the most stringent limits for downgoing nuclearites with 1.6 × 1013 GeV M 4.0 × 1015 GeV and a typical galactic velocity 0 = 10−3.

Full Text

Preamble

Exploring Detection of Nuclearites in a Large Liquid Scintillator Neutrino Detector

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Abstract

We take the JUNO experiment as an example to explore nuclearites in future large liquid scintillator detectors. Compared to previous calculations, the visible energy of nuclearites traversing the liquid scintillator will be reestimated for liquid scintillator-based detectors. The JUNO sensitivities to the nuclearite flux are then presented. It is found that the projected JUNO sensitivities can be better than $7.7 \times 10^{-17}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for nuclearite masses between 10^{15} GeV and 10^{24} GeV and an initial velocity of 10^{-3} with 20 years of running. Note that JUNO will provide the most stringent limits for downgoing nuclearites with masses above 10^{15} GeV and a typical galactic velocity $\beta_0 = 10^{-3}$.

PACS numbers: 14.80.-j, 21.65.-f, 95.55.Vj

Introduction

Strange quark matter (SQM) is a hypothetical strongly interacting matter composed of roughly equal numbers of u, d, s quarks and a small amount of electrons [1, 2]. It is believed that SQM is the true ground state of quantum chromodynamics, where absolutely stable SQM objects with baryon number A ranging from that of ordinary nuclei to neutron stars ($A \sim 10^{57}$) are expected [3]. SQM has a slightly larger density than the saturation density of ordinary nuclear matter and may be created in various astrophysical scenarios, such as the hadronization process of the early universe [2], collisions of binary compact stars [4, 5], type II supernovae driven by deconfinement phase transition [6], and even heavy ion collisions on Earth [7, 8]. SQM objects are considered cold dark matter candidates and may be present in cosmic radiation reaching Earth. Light SQM objects ($A < 10^7$) are usually called strangelets [9–13], while in this work we focus on heavier ones ($M > 10^{10}$ GeV) known as nuclearites [14, 15]. Based on their special properties, nuclearite searches have been performed through various methods: identifying seismic activities with an epilinear source on Earth [16] and the Moon [17], ionization tracks in ancient mica [18] and CR39 nuclear track detectors in the MACRO [19, 20], SLIM [21], and Ohya [22] experiments, bar excitations induced by the thermoacoustic effect in resonant bar detectors [23], Rutherford backscattering of very heavy nuclei [24–26], signatures of gravitational lensing caused by massive nuclearites [27, 28], and photons emitted when a nuclearite moves through water in the ANTARES [29] experiment and through the atmosphere in the future JEM-EUSO [30] experiment. Despite the nonobservation of nuclearites, these experiments have been able to constrain the upper limits on the flux of cosmic nuclearites.

The liquid scintillator (LS) as a detection medium in past neutrino experiments has achieved great success [31–34]. The next-generation large LS detectors JUNO [35, 36] and LENA [37] are currently under construction in China and proposed in Europe, respectively. When a nuclearite passes through the LS medium, elastic collisions between the nuclearite and ambient LS molecules will result in an overheating track. Many photons from the black-body radiation of this track can be observed by photomultiplier tubes (PMTs). Therefore, future large LS detectors have the capability to search for nuclearites. A major advantage of LS detectors is that LS wavelength shifters can absorb short-wavelength photons and reemit longer-wavelength photons. This feature ensures that LS detectors can collect more photons from the black-body radiation of the nuclearite track. Here we take the JUNO detector as an example to explore nuclearites. JUNO is a 20 kton multipurpose underground LS detector primarily designed to determine the neutrino mass hierarchy by detecting reactor antineutrinos. The JUNO detector is deployed in a 700 m underground laboratory and consists of a central detector, a water Cherenkov detector, and a muon tracker. The JUNO central detector holds 20 kton of LS in a spherical container with a radius of 17.7 m [35]. There is a 1.5 m water buffer region between approximately 18,000 20-inch PMTs, 36,000 3-inch PMTs, and the LS surface.

In this paper, we explore nuclearites in the JUNO LS detector and analyze its detection capability. Compared to previous calculations, the visible energy of nuclearites per unit track length in the JUNO LS region will be reestimated in terms of the LS fluorescence quantum yields, PMT quantum efficiencies, and the JUNO detector design. We then predict the JUNO sensitivities to the nuclearite flux. In Sec. II, we outline the main features of nuclearites and determine the maximal zenith angle below which nuclearites may pass through Earth rocks and reach the JUNO detector. In Sec. III, we analyze in detail the light yield of nuclearites traversing the JUNO LS. In Sec. IV, we present the JUNO sensitivity to the nuclearite flux based on certain conditions. Finally, discussions and conclusions are given in Sec. V.

II. The Nuclearite Energy Loss

The dominant energy loss mechanism for nuclearites passing through matter is elastic or quasielastic collisions with ambient atoms. As with meteorites, the nuclearite energy loss rate can be written as [14]

$$\frac{dE}{dx} = -\sigma\rho\beta^2,$$

where β is its velocity and ρ is the density of the traversed medium. The effective nuclearite cross section σ is given by

$$\sigma = \begin{cases} \pi R_0^2 = \pi\left(\frac{3M}{4\pi\rho_N}\right)^{2/3}, & M < 8.4\times10^{14}\mathrm{GeV}, \\ \pi\times(1\text{Å})^2 = \pi\times10^{-16}\mathrm{cm}^2, & M \geq 8.4\times10^{14}\mathrm{GeV}, \end{cases}$$

where the nuclearite density is estimated to be $\rho_N = 3.6\times10^{14}\mathrm{g\ cm}^{-3}$ [9] and the nuclearite radius R_0 can be easily derived from its mass M and density ρ_N. When the nuclearite radius $R_0 < 1$ Å ($M < 8.4\times10^{14}$ GeV), σ is dominated by the nuclearite electron atmosphere, which is never smaller than the typical atomic size with radius 1 Å [14, 38]. It is worthwhile to stress that the right-hand side of Eq. (1) should be replaced by the constant retarding force $\sigma\varepsilon$ for subsonic velocities $\beta < \beta_c = \sqrt{\varepsilon/\rho}$ with a structural energy density $\varepsilon \sim 10^9$erg cm^{-3} [14].

Based on Eqs. (1) and (2), the travel length of a nuclearite depends on its mass M, velocity β, and the medium density ρ. Some nuclearites may pass through Earth rocks and arrive at the JUNO detector, which has a 700 m rock overburden. For JUNO-detectable nuclearites, they will traverse different thicknesses of rock depending on their direction (zenith angle θ_z). In addition, one must consider the variation of Earth' s matter density. Using the PREM Earth density profile [39], we numerically calculate the maximal zenith angle $\theta_{\max}$ below which nuclearites may reach the JUNO detector, meaning their local velocity $\beta_1 > 0$ at the detector level. The corresponding results are plotted in Fig. 1 [Figure 1: see original paper] for masses from 10^{12} GeV to 10^{24} GeV and five typical initial velocities β_0 at ground level. It is clear that nuclearites from the $\theta_z = 0^\circ$ direction can reach the JUNO detector for $M > 10^{13}$ GeV and $\beta_0 = 10^{-1}$. For a typical galactic velocity $\beta_0 = 10^{-3}$, all directional nuclearites can arrive at the detector when $M > 2.5 \times 10^{22}$ GeV. Since Earth' s density changes sharply between the core and mantle, we can see knee points at $\theta_z = 146.9^\circ$ in Fig. 1.

III. The Visible Energy of Nuclearite in JUNO LS

When a nuclearite traverses the JUNO LS medium, LS molecules ($C_{18}H_{30}$) along the nuclearite path will disintegrate into their constituents due to nuclearite elastic or quasielastic collisions. These heated atoms will further collide with ambient LS molecules and generate a hot plasma shockwave [15]. The evolution of the effective temperature $T(t)$ and radius $R(t)$ of the expanding thermal shockwave can be written as [14]

$$R^2(t) = \sqrt{8}\beta_1 t R_0,$$
$$T(t) = \frac{m\beta_1 R_0}{\sqrt{8}nt},$$

where m is the LS molecule mass and $n = 48$ is the number of submolecular species. Here β_1 denotes the local velocity of the nuclearite at the detector level. The expanding cylindrical thermal shockwave can emit light through black-body radiation. The corresponding power spectrum is given by

$$\frac{d^2E}{dtd\omega} = \frac{a\omega^3}{4\pi^2 c^2 e^{\omega/kT}},$$

where ω is the angular frequency and a denotes the area of the shockwave. We can then deduce the emitted photon numbers per unit track length dN_γ/dx from the expanding cylindrical shock:

$$\frac{dN_\gamma}{dx} = \int dt \int d\omega \frac{2\pi R(t)}{\beta_1} \frac{d^2E}{dtd\omega} \frac{1}{\omega},$$

where we have used the natural system of units with $\hbar = c = k = 1$. Similarly, the total emitted energy dE_γ/dx can be directly obtained by replacing ω^2 with ω^3 in Eq. (6).

These emitted photons from black-body radiation cannot be entirely detected by the JUNO PMTs since they undergo absorption, reemission, and Rayleigh scattering processes in the JUNO LS [36]. On the other hand, the PMT quantum efficiency depends on photon wavelength. Therefore, one cannot simply use the total emitted energy dE_γ/dx or total photon numbers to describe the visible energy in the LS detector. It is convenient to calculate the visible energy if the photon electron (pe) efficiency per photon $\epsilon(\lambda)$ is available for the JUNO detector.

Based on the LAB, PPO, and bis-MSB fluorescence quantum yields [40], we adopt a combined PMT quantum efficiency curve shape from Hamamatsu PMT data (400-800 nm) [41] and a fixed 27% efficiency (250-400 nm) to calculate $\epsilon(\lambda)$ for the wavelength range 250 nm-800 nm, as shown in Fig. 2 [Figure 2: see original paper]. We assume an average 60% survival probability for reemitted photons from the detector center to the PMT surface and 75% PMT photocathode coverage. It is found that the modeled $\epsilon(\lambda)$ approaches zero for $\lambda > 640$ nm. In the absence of related experimental data, we do not include contributions from $\lambda < 250$ nm. Note that this will not significantly affect our final results.

With Eq. (6) and the photon electron efficiency ϵ from Fig. 2, we can deduce the visible energy of nuclearite per unit track length in the JUNO LS:

$$\frac{dE_{\text{vis}}}{dx} = \frac{1}{1200\text{pe/MeV}} \int_{t_{\min}}^{\infty} dt \int_0^{\infty} d\omega \frac{2\pi R(t)}{\beta_1} \frac{\omega^3}{4\pi^2} \frac{\epsilon(\omega)}{e^{\omega/T(t)}},$$

where $t_{\min}$ takes the larger of $t_0 = R_0/(\sqrt{8}\beta_1)$ and $t_1 = (l/R_0)^2 t_0$ [14] with mean free path $l \sim 2.7$ Å. In Eq. (7), we have used the fact that a 1 MeV gamma in the detector center produces on average 1200 photon electrons [35]. Based on Eq. (7), one can numerically calculate dE_{vis}/dx as shown in the left panel of Fig. 3 [Figure 3: see original paper]. It is clear that dE_{vis}/dx does not vary for $M < 8.4 \times 10^{14}$ GeV. This is because we have adopted a constant value for R_0 in Eqs. (3) and (4), i.e., the radius of the nuclearite electron atmosphere of 1 Å. In the right panel of Fig. 3, we plot the ratio of dE_{vis}/dx to dE/dx as a function of local nuclearite velocity β_1. It is found that this ratio is independent of nuclearite mass M when $M < 8.4 \times 10^{14}$ GeV. For the $M > 1.7 \times 10^{16}$ GeV case, namely $t_{\min} = t_0 > t_1$, one can easily find $dE_{\text{vis}}/dx \propto M^{1/3}$ through the variable substitution $t = t' R_0$.

IV. The Expected JUNO Sensitivities

The light signals from nuclearites can be recorded when they satisfy the JUNO trigger conditions. Here we assume a JUNO trigger threshold of 0.5 MeV within a 300 ns window for the following analyses. One may then obtain

$$\int_0^{300\text{ns}} \frac{dE_{\text{vis}}}{dx} \beta_1 dt > 0.5\text{MeV}.$$

With the help of Eqs. (7) and (8), we calculate the minimal local velocity β_{min} as shown in Fig. 4 [Figure 4: see original paper]. It is clear that the local velocity β_1 must be larger than 8.7×10^{-6} for 10^{12} GeV $\leq M \leq 10^{24}$ GeV. For a fixed initial velocity β_0 at ground level, the maximal zenith angle θ_{max} can be deduced from Eq. (1) and the requirement $\beta_1 > \beta_{\text{min}}$. In Fig. 1, we have plotted the corresponding θ_{max} with dashed lines. It is found that JUNO may detect all downgoing nuclearites (zenith angle $\theta_z < 90^\circ$) with $M > 5.0 \times 10^{15}$ GeV and $\beta_0 = 10^{-1}$. For the $\beta_0 = 10^{-3}$ case, JUNO can detect all downgoing nuclearites with $M > 6.3 \times 10^{21}$ GeV. For the $\beta_0 = 10^{-5}$ case, JUNO is only sensitive to a narrow parameter space because $\beta_1 < \beta_{\text{min}}$.

The expected number of nuclearites in JUNO can be written as

$$N_S = 2\pi(1 - \cos\theta_{\text{max}})\phi T_{\text{run}} \pi R_{\text{eff}}^2,$$

where T_{run} is the JUNO running time and ϕ is the isotropic nuclearite flux in units of cm^{-2} s^{-1} sr^{-1}. Here we require that the nuclearite track length in the LS region be larger than 5 m and derive the effective JUNO radius $R_{\text{eff}} = \sqrt{(17.7\text{m})^2 - (5\text{m}/2)^2} = 17.52$ m. The 90% confidence level (C.L.) upper limit N_{90} to the expected N_S can be derived through the following formula [42, 43]:

$$90\% = \frac{\int_{N_S=0}^{\infty} L(N_{\text{obs}}|N_S) dN_S}{\int_{N_S=0}^{\infty} L(N_{\text{obs}}|N_S) dN_S},$$

with the Poisson-based likelihood function

$$L(N_{\text{obs}}|N_S) = \frac{(N_S + N_{\text{BG}})^{N_{\text{obs}}} e^{-(N_S+N_{\text{BG}})}}{N_{\text{obs}}!}.$$

To estimate the JUNO sensitivities to the nuclearite flux ϕ, we assume the background number $N_{\text{BG}} = 0$ and take the observed event number $N_{\text{obs}} = N_{\text{BG}} = 0$ for a 20-year run. With the help of Eqs. (9) and (10), we plot the 90% C.L. flux upper limits (solid lines) for five typical initial velocities β_0 as shown in the left panel of Fig. 5 [Figure 5: see original paper]. It is clear that the JUNO sensitivities are better than $7.7 \times 10^{-17}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ for 10^{15} GeV $\leq M \leq 10^{24}$ GeV and $\beta_0 = 10^{-3}$. JUNO is only sensitive to a narrow parameter space for the $\beta_0 = 10^{-5}$ case because $\beta_1 < \beta_{\text{min}}$. In addition, the most optimistic limit (black dotted line) has also been plotted for the $\beta_0 = 10^{-3}$ case where we only require $\beta_1 > 0$ and take $R_{\text{eff}} = 17.7$ m.

To compare with the MACRO [20], ANTARES [29], SLIM [21], and Ohya [22] experimental results, we calculate the JUNO upper limit on downgoing nuclearites for the $\beta_0 = 10^{-3}$ case. Our numerical results are presented in the right panel of Fig. 5. It is clear that the JUNO sensitivity is far better than the MACRO, SLIM, and Ohya limits. Note that JUNO will provide the most stringent limit in the range of 1.6×10^{15} GeV $\leq M \leq 10^{24}$ GeV. In the most optimistic case (red dotted line), the above range can be extended to 5.0×10^{14} GeV $\leq M \leq 10^{24}$ GeV.

We have also plotted the galactic dark matter (DM) upper limit $\phi_{\text{max}} = \rho_{\text{DM}}\beta_0/(2\pi M)$ [14, 20], where nuclearites are assumed to constitute all of the local DM density $\rho_{\text{DM}} = 0.39$ GeV cm^{-3} [44]. For $M > 3.1 \times 10^{22}$ GeV, the galactic DM limit is dominant. In the future, the JEM-EUSO experiment will provide a more stringent limit $\phi < 10^{-20}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ for $M > 5 \times 10^{22}$ GeV [30].

V. Discussions and Conclusions

As mentioned in Sec. III, the photon electron efficiency per photon $\epsilon(\lambda)$ is not considered for the $\lambda < 250$ nm range due to the absence of related experimental data. If these data become available in the future, we will derive larger dE_{vis}/dx values than those in the left panel of Fig. 3. Consequently, smaller β_{min} values will be expected. The predicted sensitivities (solid lines from $\beta_1 > \beta_{\text{min}}$) in Fig. 5 will approach the most optimistic limits (the corresponding dotted lines from $\beta_1 > 0$). It is clear that our results do not change significantly for $M > 1.0 \times 10^{15}$ GeV. Note that the nuclearite mass cannot be correctly reconstructed from the incomplete $\epsilon(\lambda)$ if a nuclearite is actually detected by the JUNO LS detector. In addition, JUNO can only provide a mass lower bound for very large dE_{vis}/dx due to PMT saturation.

In conclusion, we have investigated nuclearites in the JUNO LS detector. Compared to previous calculations, the visible energy of nuclearites in the LS has been estimated in detail. We then determine the JUNO detectable range of zenith angles for nuclearite masses from 10^{12} GeV to 10^{24} GeV and five typical initial velocities β_0 at ground level. Finally, we present the JUNO sensitivities to the nuclearite flux for a 20-year run. It is found that the JUNO sensitivities to all-directional nuclearites are better than $7.7 \times 10^{-17}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ for 10^{15} GeV $\leq M \leq 10^{24}$ GeV and $\beta_0 = 10^{-3}$. For downgoing nuclearites, the expected sensitivities are much better than those from the MACRO, SLIM, and Ohya experiments in the case of $\beta_0 = 10^{-3}$. Note that JUNO will provide the most stringent limits for 1.6×10^{15} GeV $\leq M \leq 10^{24}$ GeV.

Acknowledgments

We are grateful to Jun Cao, Liang Zhan, and Shan-Gui Zhou for their very useful discussions and critical remarks. This work is supported in part by the National Natural Science Foundation of China (Grants No. 11525524, No. 11575201, and No. 11621131001), and the Strategic Priority Research Program of the Chinese Academy of Sciences under Grant No. XDA10010100.

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